

# Design Report of the Laser System for Notching $H^-$ Beam at Booster Injection RF Frequency in the 750-keV Linac

**Xi Yang and Charles M. Ankenbrandt**

*Fermi National Accelerator Laboratory*

Box 500, Batavia IL 60510

## Abstract

With the requirement for more protons per hour from Booster, the radiation is a limiting factor. The most important periods in a Booster accelerating cycle are injection and transition crossing. The laser notching  $H^-$  beam at the Booster injection RF frequency can make a bucket-to-bucket transfer from Linac to Booster possible, and this should remove most of the capture loss at injection and the early beam loss in the cycle. Besides that, the variation of the laser pulse length can change the notch length of the  $H^-$  beam such that the bucket area filled by the beam can be controlled, and this can be applied to control the longitudinal emittance of the Booster beam.

## Introduction

Adiabatically capturing the multi-turn injected proton beam in Booster not only requires the para-phase manipulation of the RF accelerating voltage (RFSUM), but also creates certain injection losses, which could become a factor of limiting the total proton output from Booster in the future. Instead of turning on RFSUM slowly after injection for the purpose of the adiabatic capture, the Linac beam can be directly transferred to the pre-existing RF bucket in Booster to further reduce the beam loss, provide that the  $H^-$  beam in Linac has been properly notched at the injection RF frequency and those notches are precisely aligned to the  $-180^\circ$  phase of the injection RF waveform.

There are several special requirements for the laser system of creating  $H^-$  beam notches in Linac. 1<sup>st</sup>, the intensity of each laser pulse must be sufficiently high to neutralize 90% (or more) of the  $H^-$  beam *via* the photo-detachment;[1-3] 2<sup>nd</sup>, the frequency of the laser pulse (micro-pulse frequency) must be precisely locked to the

injection RF frequency  $f_r$ (=38.5 MHz); 3<sup>rd</sup>, each pulse train (macro-pulse) must be long enough to cover the entire injection time; 4<sup>th</sup>, the pulse train rep-rate can be as high as the Booster rep-rate (15 Hz); 5<sup>th</sup>, and the pulse length is determined by the width of the H<sup>-</sup> beam notch. Here, the standard 12-turn injection and a 5-ns notch length are used as the design criteria for the laser system.

### Laser Energy Requirement

The photon energy ( $E_{CM}$ ) in the H<sup>-</sup> rest frame is related to the laser photon energy ( $E_L$ ) by eq.1.[1]

$$E_{CM} = \gamma \cdot E_L \cdot [1 - \beta \cos(\theta_L)] \quad 1$$

Here,  $\beta$  and  $\gamma$  are the Lorentz parameters of the H<sup>-</sup> beam, and  $\theta_L$  is the laboratory angle of the laser beam relative to the H<sup>-</sup> beam.

For a Gaussian-profile laser beam with  $N_L$  photons intercepting a Gaussian-profile H<sup>-</sup> beam of current  $I_b$  at the angle  $\theta_L$ , the yield  $Y_l$  (number of neutral hydrogen atoms produced per laser-H<sup>-</sup> beam crossing) is given approximately by eq.2.[3]

$$Y_l = \frac{I_b \cdot N_L}{\sqrt{2\pi} \cdot e \cdot \beta \cdot c} \cdot \frac{1 - \beta \cos \theta_L}{\sin \theta_L} \cdot \frac{\sigma_N(E_{CM})}{(\sigma_b^2 + \sigma_L^2)^{1/2}} \quad 2$$

Here,  $\sigma_b$  and  $\sigma_L$  are the transverse rms sizes of the H<sup>-</sup> and laser beams normal to the plane of incidence, and  $\sigma_N(E_{CM})$  is the photo-detachment cross section.

From eq.2, it is clear that the interaction region between the laser and H<sup>-</sup> beams must be chosen at a place where the transverse H<sup>-</sup> beam size is minimal. Besides, there are spaces for installing optical elements (window and mirror). There is such a place in the 750-keV Linac, as shown in Fig.1, where the transverse H<sup>-</sup> beam waist is about 0.5 mm. And the transverse laser beam size can be adjusted to match the H<sup>-</sup> beam *via* optical system.

Since the calculated photo-detachment cross section in the range of wavelength 528 nm to wavelength 1219 nm matches the experimental data quite well,[2] the 5<sup>th</sup> order curve fit of the data generates eq.3. The unit of  $E_{CM}$  is eV.

$$\sigma_N = 9.6195 \cdot E_{CM}^5 - 83.87 \cdot E_{CM}^4 + 289.66 \cdot E_{CM}^3 - 496.58 \cdot E_{CM}^2 + 422.89 \cdot E_{CM} - 139.1. \quad 3$$

Eq.1 and eq.3 can be used to calculate the photo-detachment cross section  $\sigma_N(E_{CM})$  in the design situation of wavelength  $\lambda=1064 \mu\text{m}$  (Nd:YAG laser),  $E_L=1.165 \text{ eV}$ ,  $\beta\approx 0.04$ ,  $\gamma\approx 1.001$ , and  $\theta_L\approx 90^\circ$ , and the result is  $3.745\times 10^{-17} \text{ cm}^2$ . Since the desired neutralization efficiency of the  $\text{H}^-$  beam is 90% or higher, there is a minimum requirement for the laser energy per pulse. Eq.4 is used to calculate the neutralization efficiency in a one-pass configuration.

$$\eta_b = \left( \frac{(Y_1 \cdot |e|)}{t} \right) / I_b . \quad 4$$

Here,  $e$  is the electron charge in unit of coulomb,  $t$  ( $=5\times 10^{-9} \text{ s}$ ) is the laser pulse length, and  $I_b$  is the  $\text{H}^-$  beam current in unit of ampere.

In the design situation, a laser beam crosses the  $\text{H}^-$  beam twice when an  $\text{H}^-$  beam notch is created. Eq.4 is modified to eq.5 in order to calculate the neutralization efficiency in the tow-pass configuration.

$$\begin{aligned} \eta_{bf} &= \eta_b \cdot \left( 1 + \left( \frac{(I_b - \eta_b \cdot I_b) \cdot (N_L - Y_1)}{I_b \cdot N_L} \right) \right) \\ &= \left\{ \left( \frac{(Y_1 \cdot |e|)}{t} \right) + \left( \left( I_b - \left( \frac{(Y_1 \cdot |e|)}{t} \right) \right) \times (N_L - Y_1) \times \left( \frac{Y_1}{I_b \cdot N_L} \right) \times \frac{|e|}{t} \right) \right\} / I_b . \end{aligned} \quad 5$$

The  $\text{H}^-$  beam neutralization efficiency vs. the laser energy per pulse is calculated using eq.5, and the result is shown in Fig.2. It is clear that the minimum requirement for the laser energy per pulse is  $Ep_{min}=7.25 \text{ mJ}$ . The required total laser energy per second is obtained using eq.6.

$$E_{tot} \geq Ep_{min} \cdot h \cdot N \cdot f_0 . \quad 6$$

Here,  $h$ (=84) is the RF harmonic number,  $N$  is the number of injection turns, and  $f_0$  is the rep rate.

In the situation that Booster is operated at 12-turn injection and 15-Hz rep rate, the minimum requirement for the total laser energy is  $110 \text{ J/s}$ . None of the existing laser systems can operate at such high micro-pulse and macro-pulse frequencies of 38.5 MHz and 15 Hz, and simultaneously output  $110 \text{ J/s}$ .

## Laser Cavity Design

Since the number of photons used to create an  $H^-$  beam notch is negligible (less than 0.000002%), the rest of the photons in the pulse are wasted. Taking this into consideration, one can design a laser cavity to store a laser pulse and reuse it to create as many  $H^-$  beam notches as possible before the pulse energy drops to  $Ep_{min}$ .

There are following considerations for such a laser cavity: 1<sup>st</sup>, a laser pulse (or called seeding pulse) can be switched in the cavity, kept at a certain time (injection time), and switched out the cavity; 2<sup>nd</sup>, the place where the laser and  $H^-$  beams intercept must be inside the cavity and close to one end mirror of the cavity (keeping the notch length close to the laser pulse length); 3<sup>rd</sup>, the round-trip time of the cavity must precisely match the injection RF period  $T(=1/f_{rf})$ , 26 ns; 4<sup>th</sup>, the round-trip loss must be kept as low as possible, since in the 12-turn injection situation, the 90% neutralization efficiency requires the pulse energy to be above  $Ep_{min}$  until 1008 round-trips; 5<sup>th</sup>, and depending upon how low the round-trip loss (or how high the cavity Q-factor) can be achieved, a diode-pumping system needs to be designed and installed for compensating the round-trip loss and maintaining the pulse energy above  $Ep_{min}$ .

Since we already have a Nd:YAG laser (Surelite<sup>TM</sup> I-20) from Continuum,[4] with a rep rate of 20 Hz, pulse energy of 420 mJ, and pulse-width of 5-ns in Booster, and it can be used as the seeding laser.

The diagram of the laser system for creating  $H^-$  beam notches is shown in Fig. 3. A zoom-lens system (matching optics) is used to optically match the output of the seeding laser to the fundamental cavity mode (mode#1). In the situation that the seeding pulse is p-polarized, two mirrors are used to steer the seeding pulse through a static half-wave plate into the laser cavity, where the now s-polarized pulse reflects from a Brewster plate.[5] In the case that the seeding pulse is s-polarized, the half-wave plate isn't needed. The laser cavity contains a Q-switch Pockels cell (PC), which has a  $\lambda/4$  static bias to prevent the laser cavity from free-lasing. After making two passes through the PC, the pulse is p-polarized and passes through the Brewster plate. At this time, a variable-width gate pulse changes the PC bias to zero wave before the circulating pulse comes back, and the pulse is trapped in the cavity when the PC gate is on. After the

captured pulse makes 1007 round trips, the PC gate pulse terminates, returning the PC bias to  $\lambda/4$ . On the final round trip, the pulse rotates back to s-polarization such that it reflects off the Brewster plate.

Since the round-trip time is determined by the injection rf period (26 ns), the cavity length  $L(=c \times T/2)$  is 3.9 m. LASCAD simulation code is used to determine the parameters of cavity elements which make the transverse laser-beam size match the H<sup>-</sup> beam size at the interception and simultaneously satisfy the cavity stable condition.[6] When curvatures of high-reflection (HR) mirrors #1 and #2 are 1 m and 10 m, the intensity profile of mode#1 at HR mirror#2 is shown in Figs.4. The interception between the laser and H<sup>-</sup> beams is close to mirror#2, where the radius of mode#1 nearly matches the radius of the H<sup>-</sup> beam. Besides, according to the LASCAD simulation, it is not a problem for transversely matching the size between the laser and H<sup>-</sup> beams since the radius of the cavity mode can be varied in the range of less than half to several millimeters at the interception through the adjustment of cavity elements.

### Pump System Consideration

For the pump system design, the round-trip loss  $\delta c$ , or the cavity Q, is one of the most important factors since the pulse energy needs to be kept above  $Ep_{min}$  during the 1008 round-trips, and at the same time, for the energy envelope of the seeding pulse, the cumulative effect of the energy extracted by each round-trip must be taken into consideration.

In the  $m^{\text{th}}$  round-trip ( $1 \leq m \leq 1008$ ), the initial pulse energy is  $U_{in}(m)$ , the final pulse energy is  $U_{out}(m)$ , which is equal to  $U_{in}(m+1)$  except when  $m$  is equal to 1008, and the extracted energy from the pump system is  $U_{ext}(m)$ .  $U_{in}(1)$  is the energy of the seeding pulse. The round-trip loss can be divided into transmission terms  $T_1$  and  $T_2$  on both sides of the pumping rod. We assume: 1<sup>st</sup>,  $T_1$  equals  $T_2$ , and is calculated using eq.7

$$T_1 = T_2 = T = (1 - \delta c)^{1/4}; \quad 7$$

2<sup>nd</sup>, losses inside the rod (not including interface reflections) are negligible; 3<sup>rd</sup>, losses are the same for each pass; 4<sup>th</sup>, and losses do not depend on the circulating pulse energy. The extracted energy is calculated using eq.8.

$$\begin{aligned}
U_{ext}(m) &= U_{in}(m) \cdot (T_1 \cdot G(m) - T_1 + T_1 \cdot G(m) \cdot T_2^2 \cdot G(m) - T_1 \cdot G(m) \cdot T_2^2) \\
&= U_{in}(m) \cdot T(T^2 \cdot G(m) + 1) \cdot (G(m) - 1).
\end{aligned} \tag{8}$$

Here, the gain at the  $m^{\text{th}}$  round-trip ( $G(m)$ ) is obtained using eq.9

$$G(m) = \exp(n(m-1) \cdot \sigma_{st} \cdot l_{rod}). \tag{9}$$

Here,  $\sigma_{st}(=2.8 \times 10^{-17} \text{ mm}^2)$  is the stimulated emission cross section of Nd:YAG,[] and  $l_{rod}$  ( $=140 \text{ mm}$ ) is the pumping rod length.  $n(m)$  is the population inversion at the  $m^{\text{th}}$  round-trip and is calculated using eq.10

$$\begin{aligned}
n(m) &= n(m-1) - U_{in}(m) \cdot T(T^2 \cdot G(m) + 1) \cdot (G(m) - 1) \cdot \left( \frac{1}{h \cdot \gamma \cdot V} \right) \\
&\quad - \left( \frac{n(m-1) \cdot T}{\tau_f} \right) + Wp \cdot (n_{tot} - n(m-1)) \cdot T.
\end{aligned} \tag{10}$$

Here,  $\tau_f(=250 \text{ } \mu\text{s})$  is the spontaneous fluorescence lifetime,  $n_{tot}(=4 \times 10^{17} \text{ mm}^{-3})$  is the number density,  $T$  is the round-trip time,  $V(=140 \times \pi \times 1.5^2 \approx 989.6 \text{ mm}^3)$  is the pumping volume,  $h(=6.62608 \times 10^{-34})$  is the plank constant,  $\gamma(=c/\lambda \approx 3 \times 10^8 / (0.8 \times 10^{-6}) \approx 3.75 \times 10^{14} \text{ Hz})$  is diode frequency, and  $Wp$  is the pumping rate and has a relation (eq.11) with the diode pump power ( $P_d$ ).[7]

$$P_d = \frac{(Wp \cdot n_{tot} \cdot Ep \cdot V)}{\eta_p} \tag{11}$$

Here, diode-pumping efficiency  $\eta_p$  is about 10%,  $Ep(\approx 2.4831 \times 10^{-19} \text{ J})$  is energy per photon of the pump laser.

Till now, we have all the information and tools needed for calculating the energy envelop of the seeding pulse during the 1008 round-trips. First, considering the situation without pumping and the seeding pulse energy of 0.05 J, the energy envelope is calculated at four different round-trip losses, 0.02, 0.015, 0.01, and 0.005, and the results are shown as the black, red, green, and blue curves respectively in Fig.5(a). It is clear that the energy envelope is strongly influenced by the round-trip loss, and the required pump power can be greatly reduced if the cavity Q can be improved. In the situation that the round-trip loss is 0.01, which is possible, the energy envelope is calculated at four different seeding pulse energies, 0.4 J, 0.3 J, 0.2 J, and 0.1 J, and the results are shown as the black, red, green, and blue curves in Fig.5(b). Even in the situation that the seeding pulse has the highest energy of 0.4 J, the pulse energy drops to  $Ep_{min}$  at 400 round-trips.

So the pump system is needed when the round-trip loss is 1%. Similar calculations have been done for the round-trip loss of 0.5% (challenging to get), energy envelopes at four seeding pulse energies of 0.4 J, 0.3 J, 0.2 J, and 0.1 J are shown as the black, red, green, and blue curves in Fig.5(c). Since in the case of the seeding pulse energy to be 0.4 J, the pulse energy drops to  $E_{p_{min}}$  after 800 round-trips, there is nearly no need for the pump system.

In the situation that the round-trip loss is 0.01, the pump system is needed for keeping the pulse energy above  $E_{p_{min}}$ . However, in the process of pumping, the pulse energy fluctuates in the first several tens of round-trips when the seeding pulse energy is above the threshold. As an example, when the pump rate  $W_p$  equals  $10 \text{ s}^{-1}$ , the energy fluctuation starts from the seeding pulse energy of 0.09 J, as shown by the red curve in Fig.5(d), and the energy fluctuation reaches twice of the seeding energy when the seeding pulse energy is 0.1 J, the black curve in Fig.5(d). No energy fluctuation is observed when the seeding pulse energy is 0.08 J, as shown by the green curve in Fig.5(d). The energy fluctuation could damage optical elements in the cavity when it goes too high.

After adjusting the seeding pulse energy and the pumping rate according to the criteria of keeping them as low as possible and simultaneously maintaining the pulse energy above  $E_{p_{min}}$ , the result is shown in Fig. 5(e) as the black curve.  $W_p$  is  $80 \text{ s}^{-1}$  and the CW pump power is 27 kW. The red curve is the case of no pumping.

In another scheme, two seeding lasers can be applied in such a way that after the first seeding pulse circulates 504 round-trips, the second seeding pulse is switched in the cavity in the condition of having the time synchronization and spacious match with the first pulse. The schematic diagram is shown in Fig.6. The steering mirror before the Brewster plate in Fig.3 is replaced by Brewster plate#0. Since seeding pulse#2 is adjusted to be p-polarized, it passes both Brewster plates. The optical path of seeding pulse#2 is in dash lines. An identical Q-switch (Q-switch#0) with that for the seeding pulse#1 is set in cavity #2 for seeding pulse#2, except seeding pulse#2 circulates in the cavity with s-polarization since the Brewster plate plays the role of reflecting the pulse when it is trapped. Both cavities share the common part of the cavity on the right side of the Brewster plate, including the diode-pump system (if needed) and HR mirror#2, to keep the interception between the laser beam and the H<sup>+</sup> beam at the same place. For the

round-trip loss of 0.01 and without pumping, both seeding pulses have the same energy of 0.42 J, and the simulated energy envelope is shown in Fig.7. There are about one hundred turns with the pulse energy about 5 mJ which gives the neutralization efficiency of 72%.

### Conclusion

The most important factor for the laser system of creating  $H^-$  beam notches is the Q-factor of the cavity, which is determined by the cavity round-trip loss  $\delta c$ . The major effort in the experiment is to improve the cavity Q-factor by using cavity elements with high reflection coatings and optimally aligning all the cavity elements. Afterwards, depending upon the experimentally achieved cavity Q, a diode-pump system, a two seeding-laser system, or the combination of both can be used for achieving the pulse energy above  $E_{p_{min}}$  during the injection time.

### Acknowledgements

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### References:

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- [6] <http://www.las-cad.com/>.
- [7] [www.stanford.edu/class/ee231/](http://www.stanford.edu/class/ee231/) LectureNotes.





## Zoom In, Entrance to the 90-Bend

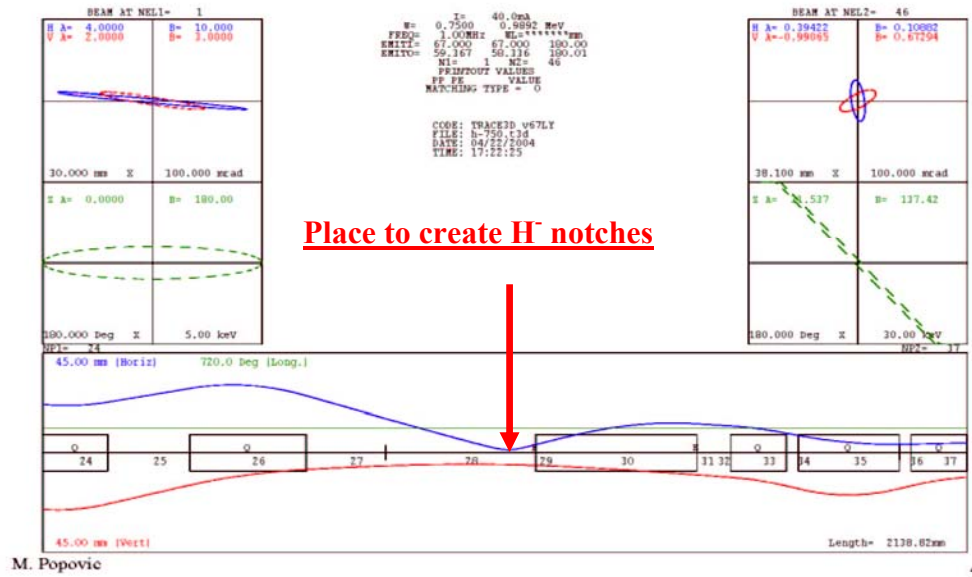


Fig. 1

Fig. 1 the simulated transverse H<sup>-</sup> beam size in the 750 keV H<sup>-</sup> line.

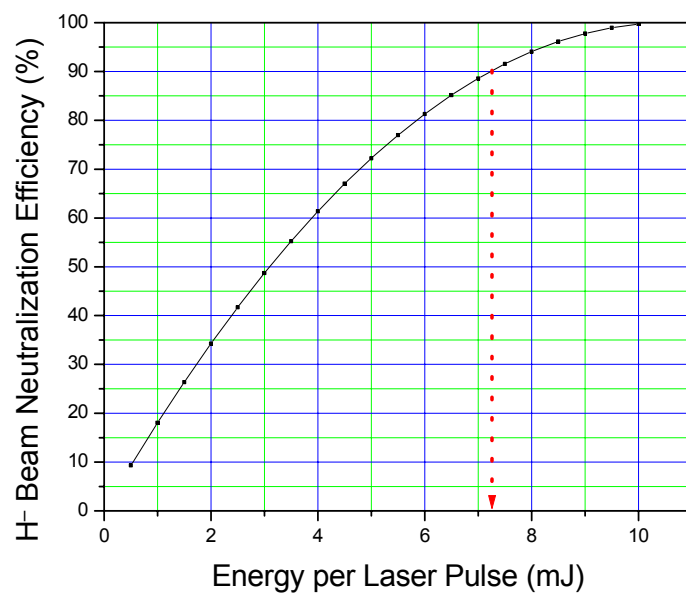


Fig. 2

Fig. 2 the  $H^-$  beam neutralization efficiency vs. the laser energy per pulse in the double-pass configuration.

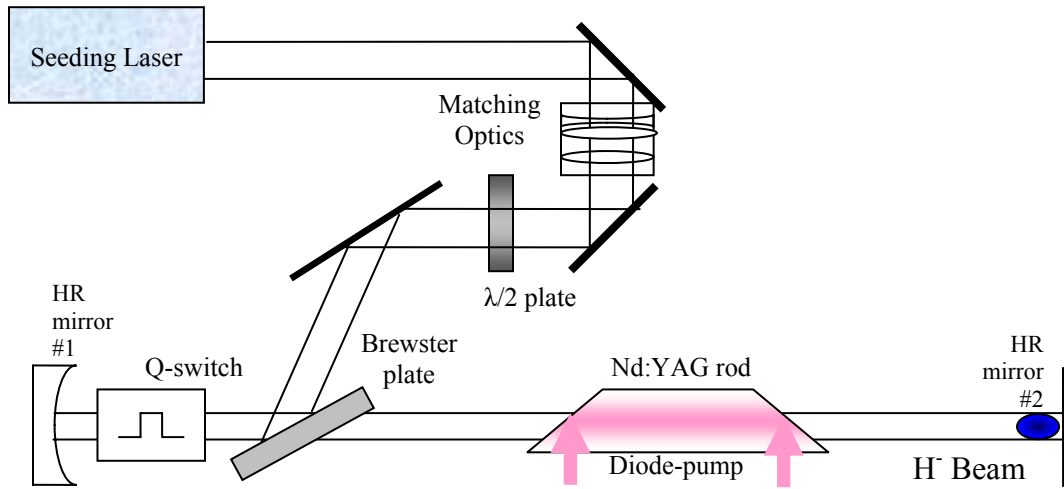


Fig. 3

Fig. 3 the diagram of the laser system for creating H<sup>-</sup> beam notches.

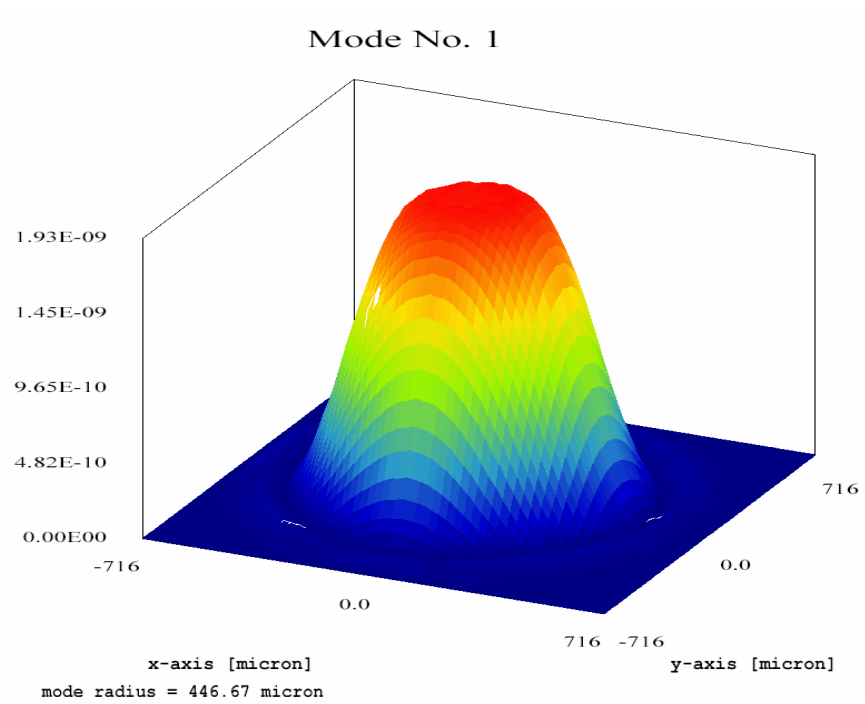


Fig. 4

Fig. 4 the simulated intensity profile of mode#1 at HR mirror#2 in Fig.3 *via* LASCAD.

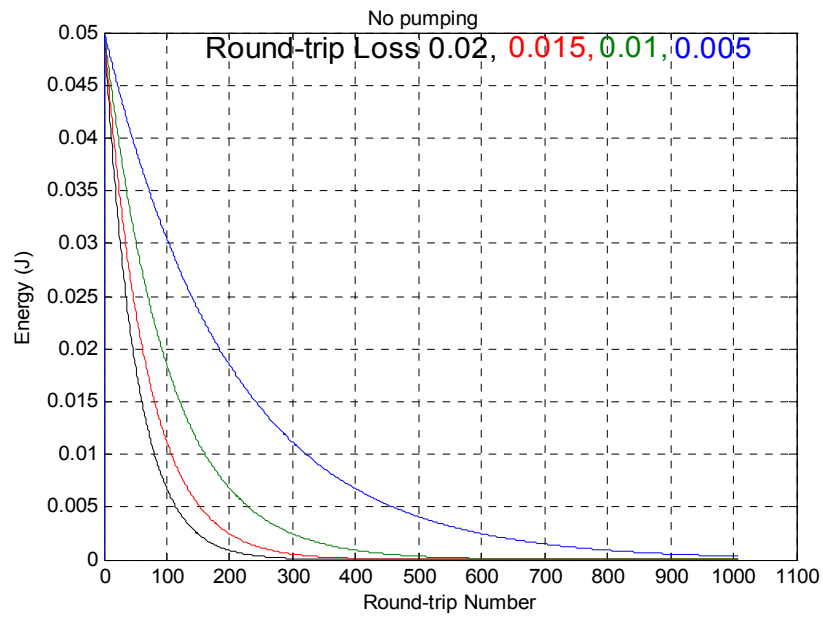


Fig. 5(a)

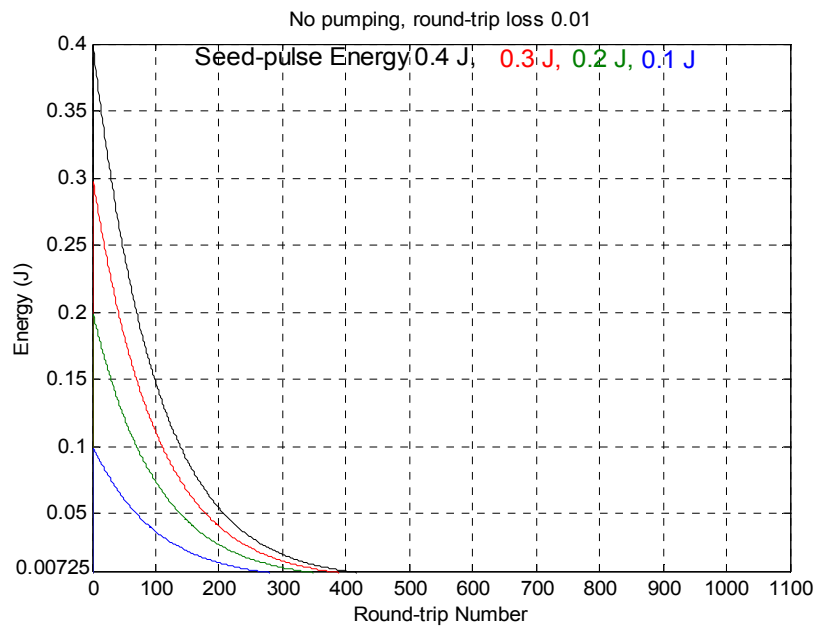


Fig. 5(b)

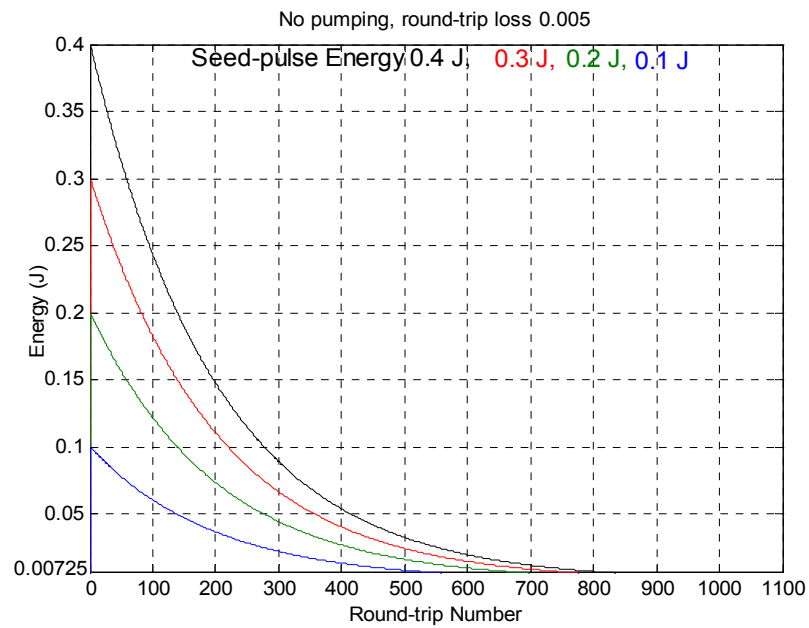


Fig. 5(c)

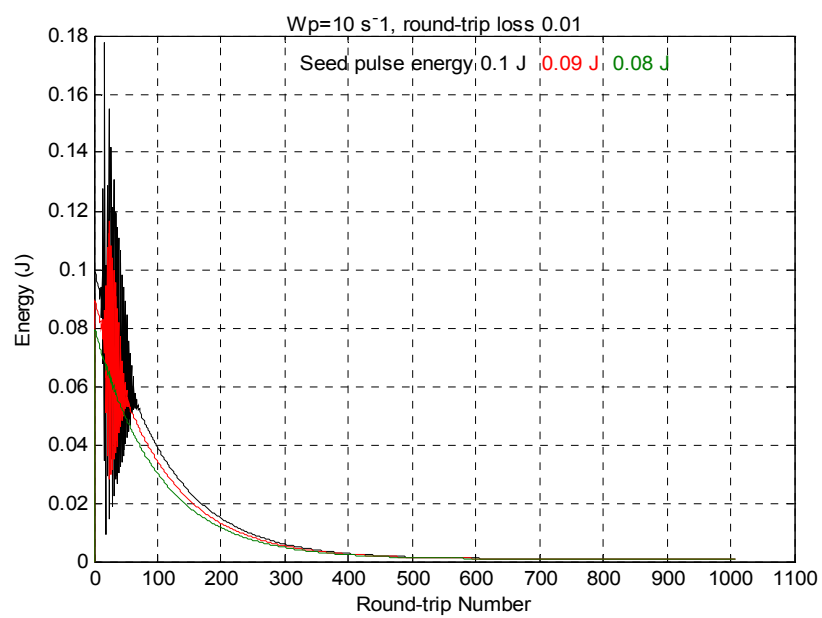


Fig. 5(d)

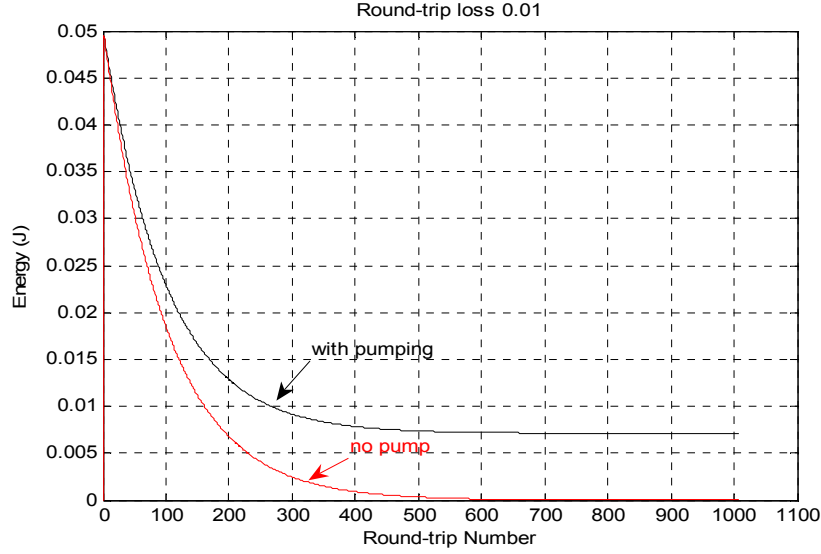


Fig. 5(e)

Fig. 5(a) simulated energy envelopes at four different round-trip losses, 0.02, 0.015, 0.01, and 0.005, without pumping, and they are represented as the black, red, green, and blue curves respectively.

Fig. 5(b) simulated energy envelopes at four different seeding pulse energies, 0.4 J, 0.1 J, 0.2 J, and 0.1 J, with a round-trip loss of 0.01 and without pumping. The results are shown as the black, red, green, and blue curves respectively.

Fig. 5(c) simulated energy envelopes at four different seeding pulse energies, 0.4 J, 0.1 J, 0.2 J, and 0.1 J, with a round-trip loss of 0.005 and without pumping. The results are shown as the black, red, green, and blue curves respectively.

Fig. 5(d) simulated energy envelopes at three different seeding pulse energies, 0.1 J, 0.09 J, and 0.08 J, with a round-trip loss of 0.01 and pumping rate  $W_p=10 \text{ s}^{-1}$ . The results are shown as the black, red, and green curves respectively.

Fig. 5(b) simulated energy envelopes at the seeding pulse energy of 0.05 J, a round-trip loss of 0.01, the black curve is the situation with  $W_p=80 \text{ s}^{-1}$ , and the red curve is the situation without pumping.

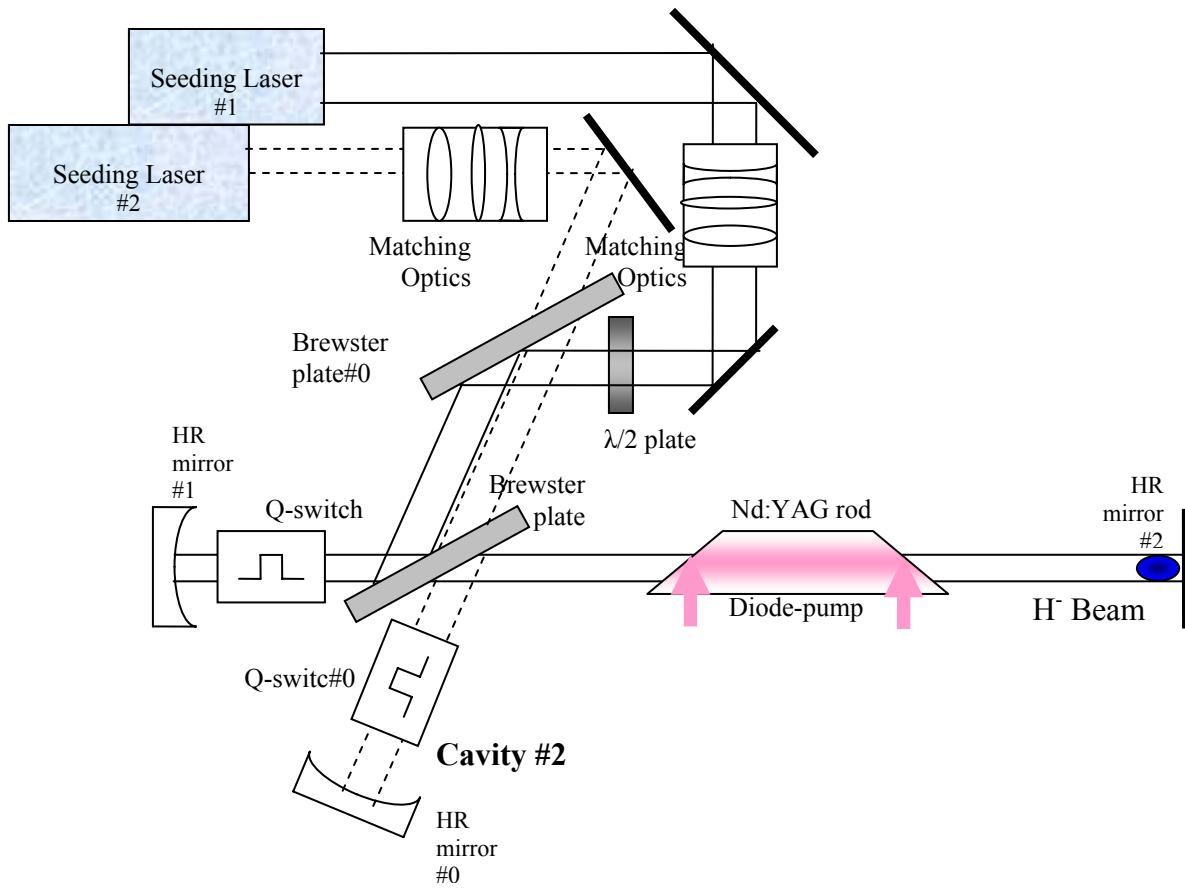


Fig. 6

Fig. 6 the laser system at the two seeding laser configuration.



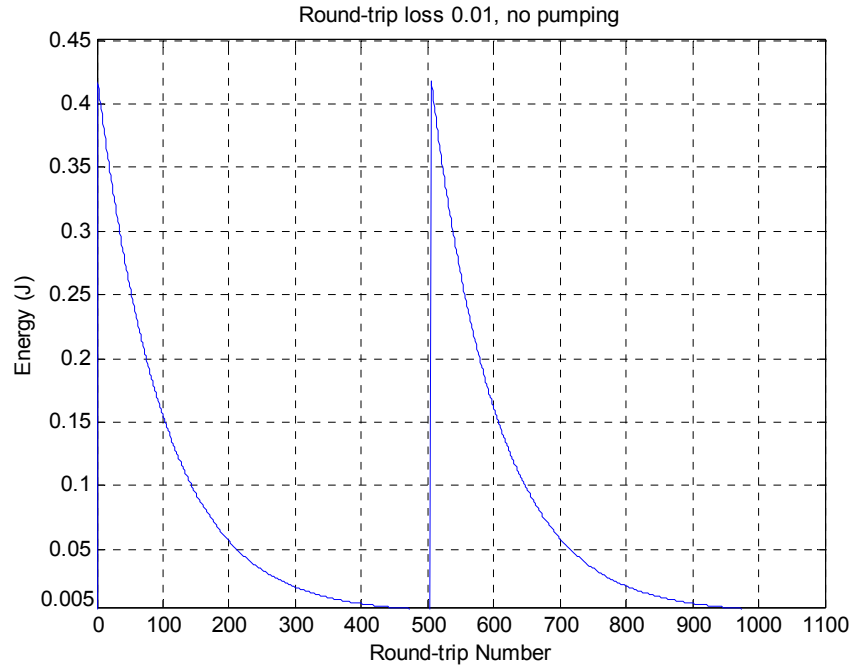


Fig. 7

Fig. 7 the simulated energy envelop at the two seeding laser configuration with the condition of the round-trip loss 0.01, no pumping, both seeding pulses having the same energy of 0.42 J.